TABLE OF CONTENTS

	Page	
INTRODUCTION	1	1/A5
HISTORY	4	1/A8
PURPOSE OF THE EXPERIMENT	5	1/A9
INSTRUMENT DESIGN	8	1/A12
VIKING SEISMIC SYSTEM	11	1/B1
SCIENTIFIC ANALYSIS	13	1/B3
RECOMMENDATIONS FOR FUTURE MISSIONS	17	1/B7
CONCLUSION	25	1/C1
REFERENCES	27	1/C3
APPENDICES		
A. LIST OF PERSONNEL		1/C9
B. SOFTWARE FILTER CONTROL		1/C10
C. PRIORITY DATA RECORDING		1/D2

APR 3 0 1981

NAS 1.26:3408

ORIGINAL

COMPLETED

NASA Contractor Report 3408

The Viking Seismometry Final Report

Andrew R. Lazarewicz, Don L. Anderson, Kenneth Anderson,
Anton M. Dainty, Frederick K. Duennebier, Neal R. Goins,
Tony C. D. Knight, Robert L. Kovach, Gary V. Latham,
Wayne F. Miller, Yosio Nakamura, George H. Sutton,
and M. Nafi Toksoz

CONTRACT NAS7-100
APRIL 1981

NASA

NASA Contractor Report 3408

The Viking Seismometry Final Report

Andrew R. Lazarewicz, Don L. Anderson, Kenneth Anderson,
Anton M. Dainty, Frederick K. Duennebier, Neal R. Goins,
Tony C. D. Knight, Robert L. Kovach, Gary V. Latham,
Wayne F. Miller, Yosio Nakamura, George H. Sutton,
and M. Nafi Toksoz
NASA Office of Space Science
Washington, D.C.

Prepared for
NASA Office of Space Science
under Contract NAS7-100

National Aeronautics
and Space Administration

**Scientific and Technical
Information Branch**

1981

TABLE OF CONTENTS

	Page
INTRODUCTION	1
HISTORY	4
PURPOSE OF THE EXPERIMENT	5
INSTRUMENT DESIGN	8
VIKING SEISMIC SYSTEM	11
SCIENTIFIC ANALYSIS	13
RECOMMENDATIONS FOR FUTURE MISSIONS	17
CONCLUSION	25
REFERENCES	27
APPENDICES	
A. LIST OF PERSONNEL	
B. SOFTWARE FILTER CONTROL	
C. PRIORITY DATA RECORDING	

INTRODUCTION

The purpose of the Viking Seismology Experiment was to determine the seismicity of Mars and define its internal structure by detecting vibrations generated by marsquakes and meteoroid impacts. The lack of marsquakes recognized in the Viking data makes it impossible to make any direct inferences about the interior of Mars and only allows the setting of upper bounds on the seismic activity of the planet. After obtaining more than 2100 hours (89 days) worth of data during quiet periods at rates of one sample per second or higher, the Viking 2 seismometer was turned off as a consequence of a lander system failure. During the periods when adequate data were obtained, one event of possible seismic or meteoroid impact origin was recognized; however, there is a significant probability that this event was generated by a wind gust. The lessons learned from Viking, however, will ensure that seismic systems on future Mars missions will have a considerably higher probability of obtaining their goals.

The Viking Seismometer is a three component short-period system designed to meet severe constraints of weight, size, power consumption, and data rates necessary for incorporation into the Viking lander (Anderson et al., 1972). Its small size and location on the lander body produced a relatively insensitive and noisy seismic system. Although the Apollo lunar seismometers have different peak frequencies (0.5 and 8 Hz) than the Viking seismometer (3 Hz), the Viking seismometer is about 1/20 the sensitivity of the Apollo seismometers at 3 Hz. Over most of the frequency band of seismological interest, the Apollo seismometers are generally 2 to 3 orders of magnitude more sensitive than the Viking seismometer. Because of lander vibrations in response to Martian winds, much of the seismic data are

contaminated by wind noise and thus unsuitable for detection of seismic events. When the winds are quiet (< 2 m/sec), background noise is below the level detectable by the system. An event of possible seismic origin (SOL 80 event) was recognized at a time when wind data suggest relatively quiet conditions. One SOL is one Martian Solar day = 24h 39m 35.25s. No wind measurements were made within 20 minutes of the event, thus it is possible that a gust could have occurred between wind samples and produced the event (Anderson et al., 1977). If it is seismic in origin, the high frequency and short duration of this event suggest, but do not require that it was generated locally (certainly within 100 km of the lander).

The detection of one local marsquake (at most) during the equivalent of 89 days of operations allows us to set limits on the probable seismicity of the planet. The probability is greater than 67% that Mars has a lower seismicity than the Earth's intraplate seismicity. If Martian seismicity is similar to intraplate seismicity on Earth (there is currently no evidence of plate tectonics on Mars), then about 2 to 3 events would have been detected (Goins and Lazarewicz, 1979).

Requirements for successful seismic experiments on Mars and other planetary objects can be met using present-day technology. These include (1) high sensitivity, dynamic range, and frequency bandwidth to allow detection of small and distant events, (2) seismometer networks to allow location of detected events and inversion of seismic parameters to obtain planetary structures, and (3) flexible data collection and compression methods to allow variation of parameters for optimum retrieval of information.

Much like the Viking seismometer on Mars, the first seismometer on the Moon (Apollo 11) was noisy and told us little about the Moon. A great wealth of information was obtained, however, by later Apollo seismometers, and we are confident that the same will be true when more advanced seismic systems are installed on Mars.

Two acronyms will be used in this report. VLS (Viking Lander Seismometer) will refer to the seismometer package alone. VLSS (Viking Lander Seismometry System) will refer to the lander body, data handling capabilities and other engineering aspects in addition to the VLS.

HISTORY

In evaluating the Viking Seismology Experiment, it is important to know the history of the experiment, and thus understand the reasons for the design limitations.

Viking was designed primarily as a biologically oriented mission. The search for extra-terrestrial life was the motivating force, and other scientific goals were secondary. The original tentative instrument list did not include a seismometer. While design changes were taking place for the Viking lander, a seismometer was proposed and accepted for the Viking mission. From the outset, the primary constraints for this instrument were weight, power and cost, in that order. Initial tests, using the Caltech engineering unit, using a crude lander model, indicated no significant difference among placing the seismometer on, under or near the lander for seismic coupling of the instrument to the surface. Any seismometer deployment mechanism would have undoubtedly exceeded any weight allocation for the seismic experiment, and would have forced a decision between a lander-mounted seismometer or no seismometer at all. Through testing and compromise, the original design evolved into the VLS which went to Mars as a 2.2 kg, 3.5 watt instrument.

The weight, power, data allocation and cost constraints for the VLSS, forced a relatively low sensitivity, narrow-band, survey experiment. It is the purpose of this report to analyze the Viking Seismology Experiment, and given what we now know, offer constructive criticism toward the future design of extra-terrestrial seismology experiments. We do not intend to attempt to redesign this experiment from hindsight.

PURPOSE

The study of a planetary object by experiment may be broadly classified in four parts: (1) atmospheres, (2) surfaces, (3) interiors, and (4) magnetospheres. Earth-based astronomical studies produce a great deal of data on atmospheres and surfaces simply because they are visible from Earth. Magnetospheres may be studied with most spacecraft in the vicinity of a planet. Due to their strong dependence on landed instrumentation, studies of planetary interiors are mostly relegated to theoretical studies supported by indirect data. Theoretical studies often produce plausible, although non-unique models, and the lack of verification by experiment impedes much further progress.

The direct studies of planetary interiors (i.e. seismic, gravity, heat flow, magnetotelluric, and orbital parameters from radar and radio data), had to wait until the lunar exploration programs began in the 1960's. On 20 July 1969, with the landing of Apollo 11 on the Moon, planetary seismology was initiated as an active science. Scientifically, this was a very important step, as seismology is one of the few experimental methods which allow direct studies of planetary interiors.

Most available information for the Earth's interior is directly due to seismic studies. Most of the gross parameters (e.g. density, velocity, and pressure) of the Earth's interior are known to within 1%; the temperature is known to within a few percent. Similarly, for the Moon, the internal structure is known reasonably well, mainly due to the Apollo seismic experiments. From the outset of the Apollo seismology experiments, and throughout the eight years of data collection, it became evident that

moonquakes are much smaller than earthquakes. For this reason, and due to the limited size of the seismometer network, little useful information on the deep lunar interior (now considered the core) is available. The high Q surface scattering layer results in very emergent (signals having a gradual onset) seismic arrivals, long codas which obscure secondary arrivals and the destruction of coherently dispersed wave trains (Goins, 1978). The lunar seismic signatures have proven to be substantially (and unpredictably) different from the Earth's, leading to the obvious inference that seismic signatures need not be similar from one planetary object to another. Although this last conclusion was not unexpected, due to the constraints on the VLS it is not unreasonable to state that the VLS was designed to sense signals which were not radically different from those observed on Earth.

The Apollo seismometer systems collected signals which were so radically different from the Earth's that they were not identified as seismic signals until after the second Apollo (12) mission; even then identification was only possible due to the high data rates (40. x 10^6 bits/Earth day) and effective real-time interaction between scientists and instruments. A similar case may be made for Mars. The fact that we have no positively identified signatures does not necessarily imply that there were no seismic events. There are two alternative possibilities: (1) seismic signals do exist in the received data, but we do not know how to recognize them, and (2) the VLSS was unable to sense (e.g. due to insensitivity) seismic signals which did arrive to the Lander 2 site. The VLSS, if placed on the Moon in place of the Apollo seismic systems, would have detected lunar seismic activity at a rate of 0.5 event per year, compared to approximately 20,000/year observed with Apollo instrumentation. In other words, the VLSS wouldn't have detected any seismic activity on the Moon.

A variety of models have been constructed for the internal structure and thermal state of Mars (Urey, 1952; Kovach and Anderson, 1965; Anderson and Kovach, 1967; Binder, 1969; Ringwood and Clark, 1971; Anderson, 1972; Binder and Davis, 1973; Johnston et al., 1974; Johnston and Toksoz, 1977; Okal and Anderson, 1978; Toksoz and Hsui, 1978). These studies generally indicate that Mars is more Earth-like than Moon-like, thus marsquakes could have similar signatures to earthquakes. However, the scattering layer and the high Q observed on the Moon strongly affect lunar seismic signatures, and similar features may also occur on Mars. In fact, if the SOL 80 event (Figure 1) is a real seismic event, then it is similar to local California seismic events (Figure 2) as recorded by a similar instrument.

In summary, the main purpose of the Viking Seismology Experiment was to determine the seismicity of Mars, and the gross nature of seismic signals, with the highest probability of success if Martian seismic signatures were Earth-like.

INSTRUMENT DESIGN

The Viking seismometer is described in detail by Miller (1977), and only a general description will be included here. The VLS is a three-axis, short-period seismometer (of a useful frequency range from 0.1 to 10 Hz) entirely enclosed in a 12 x 12 x 15 cm box, a total mass of 2.2 Kg., and drawing 3.5 watts. There are three modes of data collection: (1) High Data Rate (HDR): with a sampling rate of 20.2 samples/sec/axis, (2) Event Mode: sampling the average amplitude and number of positive going zero axis crossings at a rate of one sample/sec/axis, and (3) Normal Mode: taking a 12.7 second running average of signal amplitude and sampling every 14.85 seconds. Four sixth-order low-pass Butterworth filters (0.5, 1.0, 2.0, 4.0 Hz) are available for the HDR and Normal modes, and an amplitude sensing automatic trigger from the Normal to Event mode is available. The instrument produces 6.17×10^3, 1.47×10^5, and 1.77×10^6 bits/hour in the Normal, Event, and HDR modes, respectively. The data space available during the Viking mission was nominally 4.46×10^4 bits/hour and ranged from zero to three times the nominal amount.

The VLS, trapped between the constraints of small size and low data rates, is necessarily a narrow-band, low-sensitivity system. Furthermore, the VLS is not firmly planted on the surface of Mars and separated from the lander, but is located on the lander and is highly susceptible to wind and lander noises.

The VLS on Lander 1 failed to uncage and returned no useful data, despite repeated uncaging attempts throughout the mission. The caging mechanisms push the inertial masses against the instrument casing, thus

preventing any movement of the inertial masses and minimizing shock forces on the hinge pins during transit. A complete report on this subject was written by Knight (1977).

The Martian seismic environment, as seen by the VLS, is quiet seismically, and noisy from non-seismic sources. These conditions made the triggers ineffective and they were permanently turned off within the first ten days of operation. An important design problem in the instrument package concerned automatic triggered operation. While in the Normal mode, with the triggers enabled, an event with an amplitude greater than a preset factor over the background level automatically turns on the Event Mode. However, the first motion (an important seismic parameter) which triggered the event would be lost, as the Event Mode begins recording after the triggers turn on. Furthermore, if signals were emergent, early arrivals would be lost. The trigger circuit monitors the unfiltered seismic signals and cannot be filtered. This makes it much more sensitive to high frequencies than is desirable for the Martian environment. These problems, combined with false triggering from spacecraft noises, resulted in the atuomatic triggering option not being used throughout the mission.

Given all the constraints, the Event mode is the most useful mode. Although the HDR Mode gives more information, it can only be used for short periods of time. Without knowledge of the nature of Martian seismic events, and due to the data compression involved in the Event Mode, identification of seismic events on the signature alone was impossible. Each prospective event needed to be checked against correlation with lander events and wind gusts. Only if no correlation was made could a prospective event be labelled a seismic event. Using this criterion, no seismic events

were found save one possibility: the SOL 80 event. This conclusion points out a major problem of the Viking Seismology Experiment: positive identification of seismic events is impossible without a substantial amount of extra data and information. The Event Mode was insufficient for the Viking mission. In fact there are two problems here: (1) event detection and (2) information lost due to compression. Both problems must be analyzed further before the next mission.

The final problem to be mentioned is with the filter portion of the VLS system. A sixth-order, recursive filter requires 15 constants and 6 temporary storage buffers (see Appendix B). For the six-pole, low-pass Butterworth filters used in the VLS, only 12 constants and 6 buffers were required. These were pre-programmed to offer four different filter corner frequencies. If all 15 constants were available and in the software, they could be reprogrammed, after landing, into low-pass, high-pass, band-pass or notch filters, depending on the nature of the data received. Such programming capability was beyond the 1970 technology, but is now possible. Such flexibility would greatly enhance a seismometer system's ability to detect seismic activity, and should now be relatively easy to design and construct.

VIKING SEISMIC SYSTEM

The first point to mention is an obvious and much stated one. The seismometer should not have been placed on the lander body; had it been coupled to the planetary surface at sufficient distance from the lander so as to eliminate interference from lander noises, and preferably buried to prevent detection of meteorological disturbances (i.e. wind and thermal variations) then seismic signals would have been considerably easier to detect. Approximately half of the total seismometer data allocation over the entire mission was unusable because of wind noise. Spurious events needed a thorough check of all spacecraft activities and were generally attributed to mechanical noises on the lander. Assuming approximately 2000 hours of Event Mode was spent in collecting wind and spacecraft noise, then approximately 300. x 10^6 bits of data were not usefully utilized. This is approximately 7.4 times the total recorded data budget available at any given time on the lander tape recorder (approximately 40. x 10^6 bits). In a severely limited data environment as was available during the Viking mission, this is a high price to pay. The data space lost to noise strongly offsets the financial and engineering savings incurred by leaving the seismometer on top of the lander.

The correlation process between seismometer and other spacecraft activities was made considerably more difficult by the inconsistency of the local lander time (LLT) as interpreted by different experiments and engineering analyses (a mission operations problem). It was not unusual to find substantial time differences between two reductions of the same lander clock data. For accurate seismic detection, signals received by the

seismometer should be timed and compared with other lander activities to within one sampling period of the seismometer, or a maximum of one second in this case.

With the VLS placed on the lander, it was imperative to understand, at least qualitatively, the mechanical transfer function of the lander at detectable frequencies. Tests performed at the Martin Marietta Aerospace Corp. in January 1975 to gain this information failed because of problems with the digital system. Some information was available in analog form at frequencies greater than 8 Hz. Modification of the VLS due to a lander body resonance discovered at 10 Hz, used up the financial budget available for further testing. Viking went to Mars without the Seismology Team knowing the lander response function, either in terms of frequency response or cross-talk among the three channels.

SCIENCE ANALYSIS

The purpose of any extra-terrestrial seismic experiment is to determine the dynamics, internal structure, microseismic activity (background seismic level, sources and frequency dependence), meteorite influx rate and nearby mechanical soil properties of the planetary object. The goals of the Viking Seismology Experiment have been described in more detail by Anderson et al. (1972).

The scientific results of this experiment have already been published (Anderson et al., 1976; Anderson et al., 1977). These results are still essentially correct, although considerably more data have been acquired since then. Several associated research papers have been published recently (Toksoz and Johnston, 1977; Okal and Anderson, 1978; Toksoz and Hsui, 1978; Goins and Lazarewicz, 1979; Lazarewicz and Miller, 1979) which expand on the two main Seismology Team publications. For detail on the science analysis, the reader is referred to the above publications. It is important, however, to summarize what was and was not accomplished.

On the positive side, we have learned that the background microseism level is low, below our detection threshold. As a result, wind noise (as was expected) dominated our noise data. The direct, and very important, implication is that a seismometer of much higher sensitivity can be used and that it must be isolated from meteorological disturbances. From the 19 months of successful operation of the Viking 2 seismometer, three months (approximately 2100 hours) of low noise data in one of the modes capable of seismic detection were obtained. Thus only 16% of the total operation time resulted in useful data.

The SOL 80 event is the only identified candidate for a natural seismic event. All known mechanical lander activities have been ruled out as the source for this event, and although the wind is below the seismometer's detection threshold for a few hours on each side of the event, wind data were not acquired within 20 minutes of the event. Wind gusts have been observed during such quiet periods, however, and a gust could be the source of this event. On the other hand, the SOL 80 event could be a natural seismic event. Figure 2 shows the SOL 80 event compared with two California events recorded by a similar instrument. The similarity of the three events is striking. If the Utopia Planitia region (location of the Viking 2 lander) is similar in seismic properties to Southern California, then a magnitude 3 marsquake at a distance of 110 km is consistent with the SOL 80 signature. The high frequency content (8-10 Hz) of the SOL 80 event is higher than in wind gusts showing similar seismometer signatures (Figure 3). Furthermore, with reasonable assumptions, if the three visible peaks are caused by seismic reflections, then the depth to the first significant seismic discontinuity in Utopia Planitia is approximately 16 km (Anderson et al., 1977). As the SOL 80 event is not inconsistent with either a natural seismic event nor a wind gust, neither source can be ruled out. The opinions of the various members of the Seismology Team vary greatly as to which is the source of the SOL 80 event, but the consensus is that the SOL 80 event is a potential marsquake or meteoroid impact.

If the SOL 80 event is a local seismic event, then the local events on Mars are similar to local events on Earth. This is an important conclusion which requires verification by future experimentation.

With 0 to 1 event recorded, a determination of Martian seismicity is not statistically significant; however, some useful comments may be made. If the SOL 80 event is a seismic event, then with a 67% probability, Mars has a lower seismicity than the Earth's intraplate seismicity. This probability rises to 90% if the SOL 80 event is not a natural seismic event. With 99% confidence, Mars is less seismically active than the total seismicity of Earth. These are updated values from Anderson et al. (1977), estimated by Goins and Lazarewicz (1979). If Mars has the same seismicity as the Earth's intraplate seismicity, uniformly distributed over the planet, then 2 to 3 events should have been detected (Goins and Lazarewicz, 1979).

The Viking seismology data, thermal history calculations (Toksoz and Hsui, 1978), photo-geologic data (Carr, 1974), gravity and topography data (Phillips and Saunders, 1975; Sjogren et al., 1978; Sleep and Phillips, 1979) and elastic flexure theory as applied to Olympus Mons (Thurber and Toksoz, 1978) and the lack of evidence for plate tectonics, all indicate a thick lithosphere for Mars. We therefore expect a quieter seismic environment than on Earth.

On the negative side, the loss of the Viking 1 seismometer (failure to uncage) not only meant the loss of one of two instruments, it also precluded the detection of the same event by both seismometers. Our estimate is a 75% loss of potential science due to this failure. Henceforth, any references made about the operation of the VLS will be implicitly referred to Lander 2, which did uncage successfully. With the potential exception of the SOL 80 event, we do not know the nature of local events, their signatures, or crustal thickness. With the lack of teleseismic events, we have no data on the nature of teleseisms, core size or regions of partial melting.

With an eye on the future, it is reasonable to expect continued extra-terrestrial seismic experimentation. To this end, it is necessary to set goals which are scientifically important, technically feasible and reasonably limited in scope. We recommend the designing of future Martian seismic experiments to address the following problems in light of our current knowledge:

(1) Determine the spatial distribution of seismicity and its implications for current Martian tectonic activity.

(2) Determine the velocity-depth relationship and the location of major seismic discontinuities on Mars.

(3) Determine the state (liquid or solid) and the size of the Martian core.

(4) Locate partially molten areas (if any) within the Martian interior, particularly within the upper mantle.

(5) Concentrated study of the tectonic state of, thus potentially the stresses in and around, the Tharsis area.

Problem 1 can be solved with a network of sensitive sesimometers emplaced on the surface of Mars. Problem 2 can use almost any kind of seismic data, thus is easily compatible with the other four areas. Okal and Anderson (1978) have studied problems 3 and 4 and have outlined feasible seismic studies to resolve these two problems. Problem 5 can be solved with a small seismic array in the Tharsis region.

RECOMMENDATIONS FOR FUTURE MISSIONS

The Viking Seismology Experiment, although not as scientifically productive as had been hoped, was a valuable source of experience in performing extra-terrestrial seismology. This was the first seismic experiment on an unmanned, extra-terrestrial mission. It was expected that the constraints on mass, power and data allocation, and physical location on the spacecraft would compromise the scientific results. The amount of compromise and specific problems became well understood only after the landings on Mars. In this sense, one of the major accomplishments of this experiment was an improved ability to design similar future missions. Four specific recommendations are now presented. We feel all four are necessary, technically feasible and will significantly improve future extra-terrestrial seismic experimentation.

1. Isolation from noise

We know of three noise sources on Mars: lander activity, thermal noise and wind noise. A seismic package should be isolated from all three as well as possible.

This the most important recommendation. A first seismic experiment on a planetary object searches for seismic signals of unknown character. Any detected signal must be thoroughly analyzed to determine its origin and thus classify it as a seismic signal or noise. A landed spacecraft is necessarily noisy, and the analysis and categorization of the noise adds greatly to the effort, time and money spent for data analysis.

The emplacement of a seismometer on a planetary object is not as straightforward a problem as on Earth. Construction of a seismic vault is presumably impossible, even searching for a good site (if one can get to it) is a difficult

process. It is reasonable to assume the existence of a surface layer, probably of unknown or poorly understood properties, separating the surface from bedrock (if any). This surface layer will probably modify, possibly severely, an incident seismic signal (as it did on the Moon), thus making interpretation of seismic signals that much more difficult. Furthermore, the surface layer undergoes diurnal changes of temperature with the associated thermal fluxes and changes in the thermal state of a surface seismometer.

Constructing a seismometer package showing a small cross-sectional area to the wind, and planting it on the surface of Mars, should increase the threshold for wind noise to 300 m/s. The sensitivity of the seismometer could be increased by 4 orders of magnitude and the seismometer would still be free of wind noice (Anderson et al., 1977).

The ultimate goal is total isolation from spacecraft and surface noise sources. In order of importance, a planetary seismometer must have its sensors (a) physically separated from the spacecraft, (b) buried, and (c) attached to bedrock (if any). It may be possible to couple seismometer emplacement with a coring mission. After a core is removed from a hole dug by a lander, the hole could be filled with an instrument package containing seismic and other sensors. An instrument package could also be buried with a corer. Alternatively, a penetrator mission could easily carry a seismometer, and bury the instrument at each landing site.

2. Seismometer networks in seismically active areas

The Earth and the Moon have been found to have spatial seismic and aseismic zones. Mars is also expected to be heterogeneous in seismic activity. Most notably, the Tharsis area is expected to contain stresses which should produce seismic activity even if it is in isostatic balance (Sleep and Phillips, 1979), thus seismic activity in this area might be higher than elsewhere on

the planet. There are no planetary objects where a uniform surface seismicity is expected. The strength of seismic signals received by a seismometer generally decreases with distance; as a result, a strong bias exists for sensing the seismicity of the immediate area. The Viking seismometer was placed in the relatively unexciting Utopia Planitia (for spacecraft landing safety), where substantial seismic activity was not expected. Theoretical considerations of Martian seismicity, and the physical limitations of the VLSS, place 80% of the detectable events within 10 degrees (590 km) of the lander, and a magnitude greater than 9 would be required in the Tharsis region for detection by Lander 2 (Goins and Lazarewicz, 1979). Obviously, the location of a seismometer on a planetary object is very important.

A single seismometer, especially without detailed knowledge of the nature of seismic signals, is insufficient for determining the location and nature of the seismic source. A network of seismometers offers many advantages over a single instrument, depending on how the network is deployed. Three useful types of seismic networks are:

(a) Sub-wavelength network: sensors closely spaced (within a fraction of a wavelength) so that the signal time of arrival as the different instruments is nearly simultaneous. The signals may be added, reinforcing the coherent signals through constructive interference, while weakening the incoherent signals (noise). In this fashion, the signal-to-noise ratio is improved as the $\sqrt{n}$ where n is the number of sensors.

(b) Local network: sensors are widely spaced, relative to wavelength, so that the arrival time differences are much greater than the measurable time resolution, but the instrument separation is much

less than the planetary radius. With proper adjustment of the relative phases of incoming signals, this phased network becomes a "steerable beam" for distant events, where azimuthal direction can be calculated for a given signal, or a preferential azimuth for a particular study can be chosen. Local seismic events can be located directly by triangulation and/or travel-time difference analysis.

(c) Planetary network: the network is spread throughout the entire planetary surface. This network allows for studies of heterogeneity in seismicity and interior structure, as well as focal mechanism studies. This approach has the added feature (and complication) of having instrumentation in different geological provinces.

By far, the best system is a combination of all three types. If practical constraints do not allow for a combined system, some type of network is nevertheless desirable. The simplest network is one seismometer with every landed package a c-type array (such as Apollo). A penetrator mission could deploy a planet-wide c-type network. A planetary rover could emplace a b-type network, for example, three seismometers separated by one kilometer. Obviously, the more members in the network, the better the resulting resolution.

3. Flexibility through software control

The VLS has a sixth-order, low-pass Butterworth filter with four selectable corner frequencies. The amplifier used is equivalent to a seventh-order transfer function. The corner frequencies and rolloffs could, in principle, be under software control (see Appendix B). The ability to control these from Earth would greatly increase the flexibility of the whole system, and

could be used to filter in or out, particularly desirable or undesirable signals. The 10 Hz resonance discovered during the End-to-End Test, if excited, would have been devastating for the seismology experiment. The sensitivity of the amplifier at 10 Hz was decreased at the cost of the second planned seismometer End-to-End Test. Had the amplifier parameters been software-adjustable, a major modification effort would have been replaced by a minor software change.

The sampling rate of an instrument depends on the frequency band of interest and data constraints. The sampling rate must be more than twice the upper frequency limit to prevent aliasing. The ability to modify the recorded sampling rate could be used to save data space. If data compression is used, similar software modification of the degree of compression could also be used.

4. Event detection, data collection and compression

An important aspect of seismic data is that more than 90% of the data is relatively uninteresting. Important information comes in bursts at random and unpredictable times. While Apollo could afford to send all its seismic data back to Earth, where relative importance could be determined at the leisure of scientists, Viking did not, and future planetary seismic experiments probably will not, have this luxury. Decisions on information content will have to be made before the data are returned to Earth. It is important to maximize the scientific content in the available data space: however, it will probably not become evident how to best accomplish this goal until after the experiment package is placed on another planetary object.

In order to sample three axes at a sampling rate of 20 Hz, 8 bits per sample over a 24-hour period, a seismometer system requires 41.5×10^6 bits

plus overhead (e.g., data management, time codes). Estimating 3% of the data space for overhead, or 1.2×10^6 bits, a total of 42.7×10^6 bits are required. The Viking seismometer was allocated a nominal 1.1×10^6 bits per SOL, in other words, a 39:1 reduction from optimum in data allocation. There are three immediately obvious approaches to this problem: (1) increase the data allocation, (2) devise a data compression technique where only the most important parts of a given seismic event are kept, and (3) devise a priority system of data storage which eliminates unwanted noise and periods of low information when more informative data are encountered.

The total data allocation for a given spacecraft is entirely constrained by the state of the art of data storage and transmission capabilities. This is a spacecraft system constraint and is mostly a problem of engineering and economics. Dividing the total data allocating among the various experiments will, for the foreseeable future, leave any seismology experiment far short of the optimum 42.7×10^6 bits/day. This forces optimization of the in situ data collection, processing, compression and transmission schemes.

This recommendation, although a very important one, has no known straightforward or obvious solution. Many different approaches are possible and much research must be done well ahead of the next mission so that a system may be developed and ready when the time for hardware development arrives (normally around the time of mission approval). It is important to note that the primary target for this study is in situ data management. Appendix C is an example of an approach to this problem. It includes a proposal by the Bendix Aerospace Corp. for data management in an eventual penetrator mission. This appendix is included as an illustration of a possible and promising approach to this recommendation, and is not intended as a formal recommendation.

The Viking seismometer utilized three modes of data collection previously described in the section on instrument design and by Miller (1977). The Normal mode is only useful for measuring the average background noise. With this information, the higher data rates may be used during times of low noise, and gain settings may be chosen accordingly. The "Normal" mode is virtually useless as far as returning seismic information. The Event mode was the most used mode in the Viking experiment since the normal data allocation allowed Event recording for approximately seven hours per SOL. During the high data allocation periods (approximately 3×10^6 bits/SOL), it was possible to record in the Event mode throughout the entire SOL, less the time where the seismometer was inhibited from data collection due to conflicting lander activities. It was in this mode that most of our 2100 hours of useful data were recorded, and the SOL 80 event observed. Three problems were encountered in this mode: 1) The one-second sampling rate is at least an order of magnitude less than optimum. It is strongly desired to have a time resolution of 0.1 second or better. 2) When the Event mode was automatically triggered on from the Normal mode, the first motion information was lost, and Event recording began about two seconds after the trigger. Since the triggered option was not used throughout the mission, this problem does not apply to the 2100 hours of useful data collected. 3) Because of the new seismic environment and data compression scheme, it was very important to rule out all known non-seismic sources before positive identification could be made. If the SOL 80 event had been recorded in the HDR mode, positive identification, one way or the other, may have been possible; however, the HDR mode would have filtered out some or all of the high frequency content that is a distinguishing characteristic of the SOL 80 event. The conclusion is that

the Event mode, unable to unambiguously record seismic data, is inadequate for future extra-terrestrial seismic exploration, and further work on seismic event detection and compression is necessary. Finally, the HDR mode, by far the best mode available, required too much data space, and would fill the nominal data allocation in about 40 minutes. Since coverage was highly desired over as large a time period as possible, the HDR mode was only sporadically used.

CONCLUSION

In conclusion, the most severe problems encountered in the Viking mission were, in order of importance:

1) Failure of the Lander 1 seismometer
2) Wind noise due to the location of the seismometer in the spacecraft
3) Inadequate data compression techniques
4) Low sensitivity

It is a straightforward task to eliminate all four problems for future extraterrestrial seismometry experiments. We put forward two sets of recommendations for future work on Mars:

1) Scientific Goals - to determine
    a) seismicity
    b) velocity-depth relationships
    c) nature of the core
    d) location of partially molten areas
    e) tectonic state of the Tharsis area
2) Engineering Goals - to achieve
    a) isolation from noise
    b) emplacement of seismometer networks
    c) flexibility in software control
    d) improvement of <u>in situ</u> data handling

All of these recommendations are necessary and technically feasible.

ACKNOWLEDGMENTS

We thank NASA for sponsoring this experiment (NASA grant NAS 1-9703) and the many members of the Viking Flight Team, too numerous to mention, who have contributed their time and effort in our pursuit of a successful experiment.

REFERENCES

Anderson, D.L. (1972) Internal constitution of Mars, J. Geophys. Res. 77, 789-795.

Anderson, D.L., Kovach, R.L. (1967) The composition of the terrestrial planets, Earth Planet. Sci. Lett. 3, 19-24.

Anderson, D.L., Kovach, R.L., Latham, G., Press, F., Toksoz, M.N., Sutton, G.H. (1972) Seismic investigations: The Viking Mars Lander, Icarus 16, 205-216.

Anderson, D.L., Duennebier, F.K., Latham, G.V., Toksoz, M.N., Kovach, R.L., Knight, T.C.D., Lazarewicz, A.R., Miller, W.F., Nakamura, Y., Sutton, G.H. (1976) The Viking seismic experiment, Science 194, 1318-1321.

Anderson, D.L., Miller, W.F., Latham, G.V., Nakamura, Y., Toksoz, M.N., Dainty, A.M., Duennebier, F.K., Lazarewicz, A.R., Kovach, R.L., Knight, T.C.D. (1977) Seismology on Mars, J. Geophys. Res. 82, 4524-4546.

Binder, A.B. (1969) Internal structure of Mars, J. Geophys. Res. 74, 3110-3117.

Binder, A.B., Davis, D.R. (1973) Internal structure of Mars, Phys. Earth Planet. Interiors 7, 477-485.

Carr, Michael H. (1974) Tectonism and volcanism of the Tharsis region of Mars, J. Geophys. Res. 79, 3943-3949.

Goins, Neal (1978) Lunar Seismology: The Internal Structure of the Moon, Ph.D. Dissertation, Massachusetts Institute of Technology.

Goins, N.R., Lazarewicz, A.R. (1979) Martian seismicity, Geophys. Res. Lett., in press.

Johnston, D.H., Toksoz, M.N. (1977) Internal structure and properties of Mars, Icarus 32, 73-84.

Johnston, D.H., McGetchin, T.R., Thomas, R., Toksoz, M.N. (1974) The thermal state and internal structure of Mars, J. Geophys. Res. 79, 3959-3971.

Knight, T.C.D. (1977) VL-1 seismometer failure-to-uncage, failure analysis, unpublished Martin Marietta Aerospace report.

Kovach, R.L., Anderson, D.L. (1965) The interiors of the terrestrial planets, J. Geophys. Res. 70, 2873-2882.

Lazarewicz, A.R., Miller, W.R. (1979) Digital synthesis of analog systems, Geosci. Electr., submitted.

Miller, W.F. (1977) The Viking seismometer, Instr. Soc. Am. Proc. of 23rd Intl. Instr. Symp., Las Vegas, Advances in Test Measurement 14, 325-330.

Okal, E.A., Anderson, D.L. (1978) Theoretical models for Mars and their seismic properties, Icarus 33, 514-528.

Phillips, R.J., Saunders, R.S. (1975) The isostatic state of Martian topography, J. Geophys. Res. 80, 2893-2898.

Ringwood, A.E., Clark, S.P. (1971) Internal constitution of Mars, Nature 234, 89-92.

Sjogren, W.L., Wimberly, R.N., Cain, D.L., Brenkle, J.P. (1978) Mars gravity: Additional resolution from Viking orbiter 1, Proc. Lunar Planet. Sci. Conf. 9th, 3561-3573.

Sleep, N.H., Phillips, R.J. (1979) An isostatic model for the Tharsis Province, Mars, Geophys. Res. Lett., submitted.

Thomas, D., Perkins, D. (1977) Mars Penetrator Instrument Interface Study, Final Report for NASA Ames Research Center, Contract NAS 2-9649 to the Bendix Aerospace System Operation.

Thurber, C.H., Toksoz, M.N. (1978) Martian lithospheric thickness from elastic flexure theory, Geophys. Res. Lett. 5, 977-980.

Toksoz, M.N., Hsui, A.T. (1978) Thermal history and evolution of Mars, Icarus 34, 537-547.

Toksoz, M.N., Johnston, D.H. (1977) The evolution of the moon and the terrestrial planets, in the Soviet-American Conference on Cosmochemistry of the Moon and Planets, Part 1, 295-327.

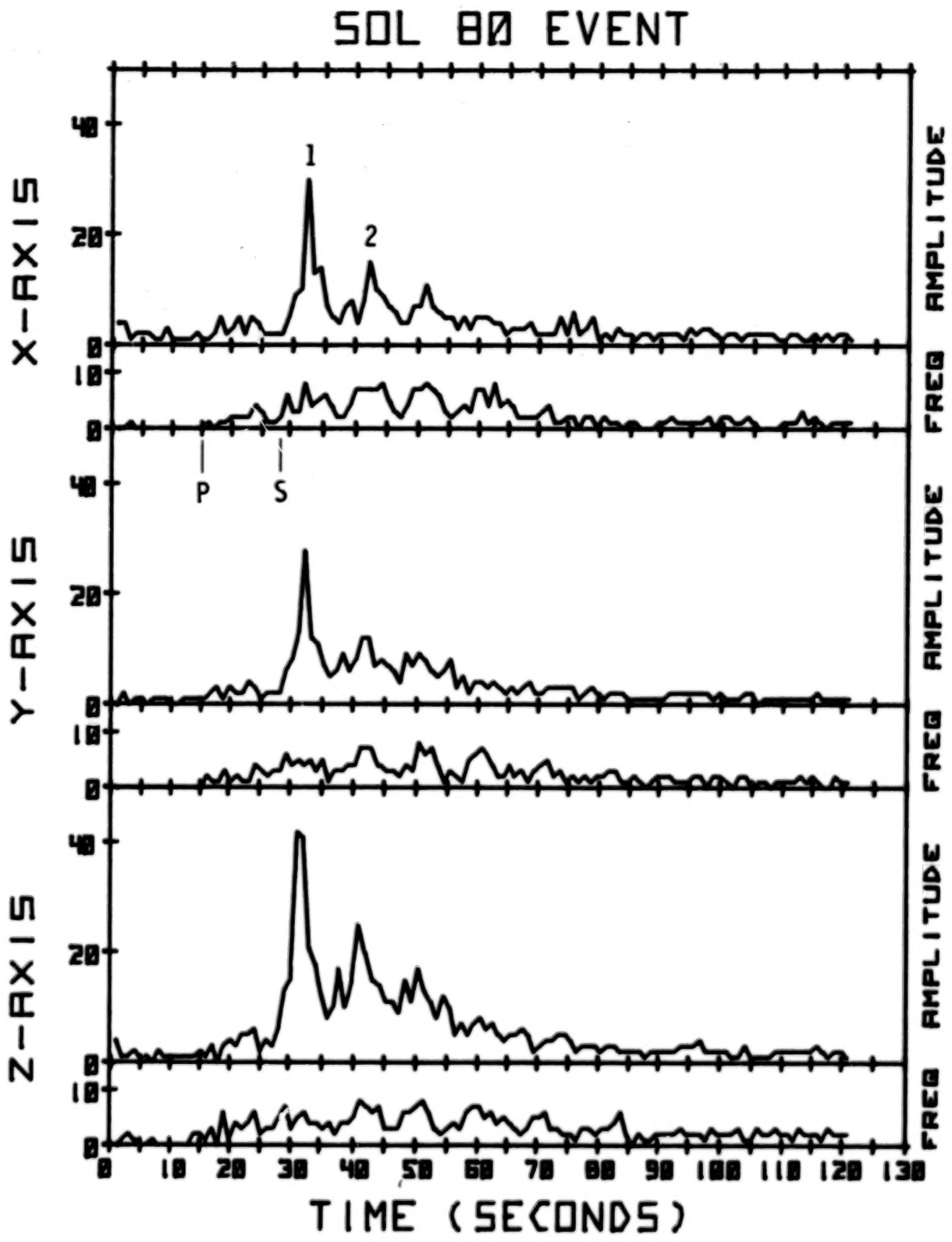
Urey, H.C. (1952) The Planets, Their Origin and Development. Yale University Press, New Haven, Connecticut.

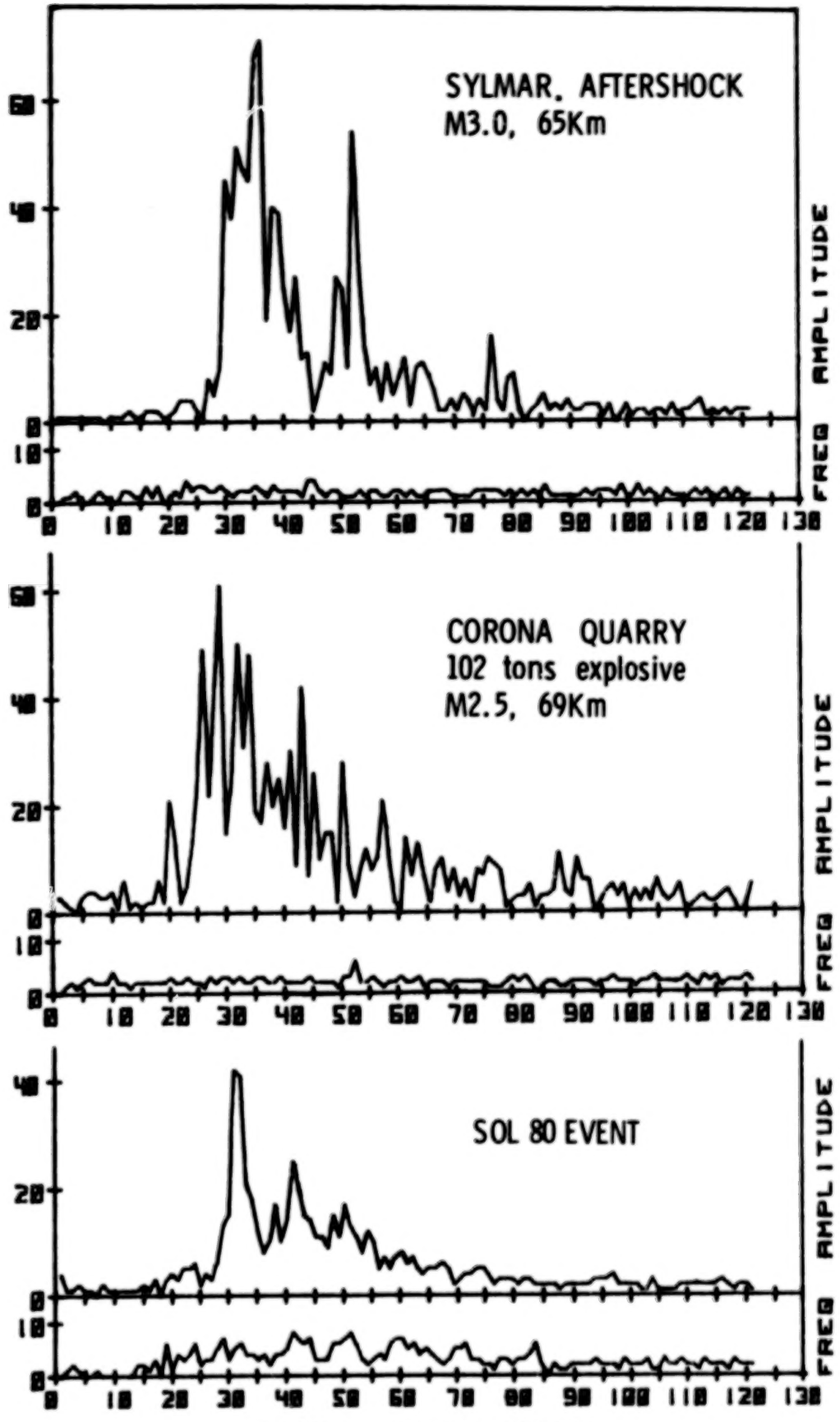
FIGURE CAPTIONS

Figure 1. The SOL 80 event as recorded on all three axes. The P and S refer to the possible arrivals of compressional and shear waves. The peaks labeled 2 and 3 are possible reflections from a seismic discontinuity, if you are brave enough to make such picks from a single record (Anderson *et al.*, 1977).

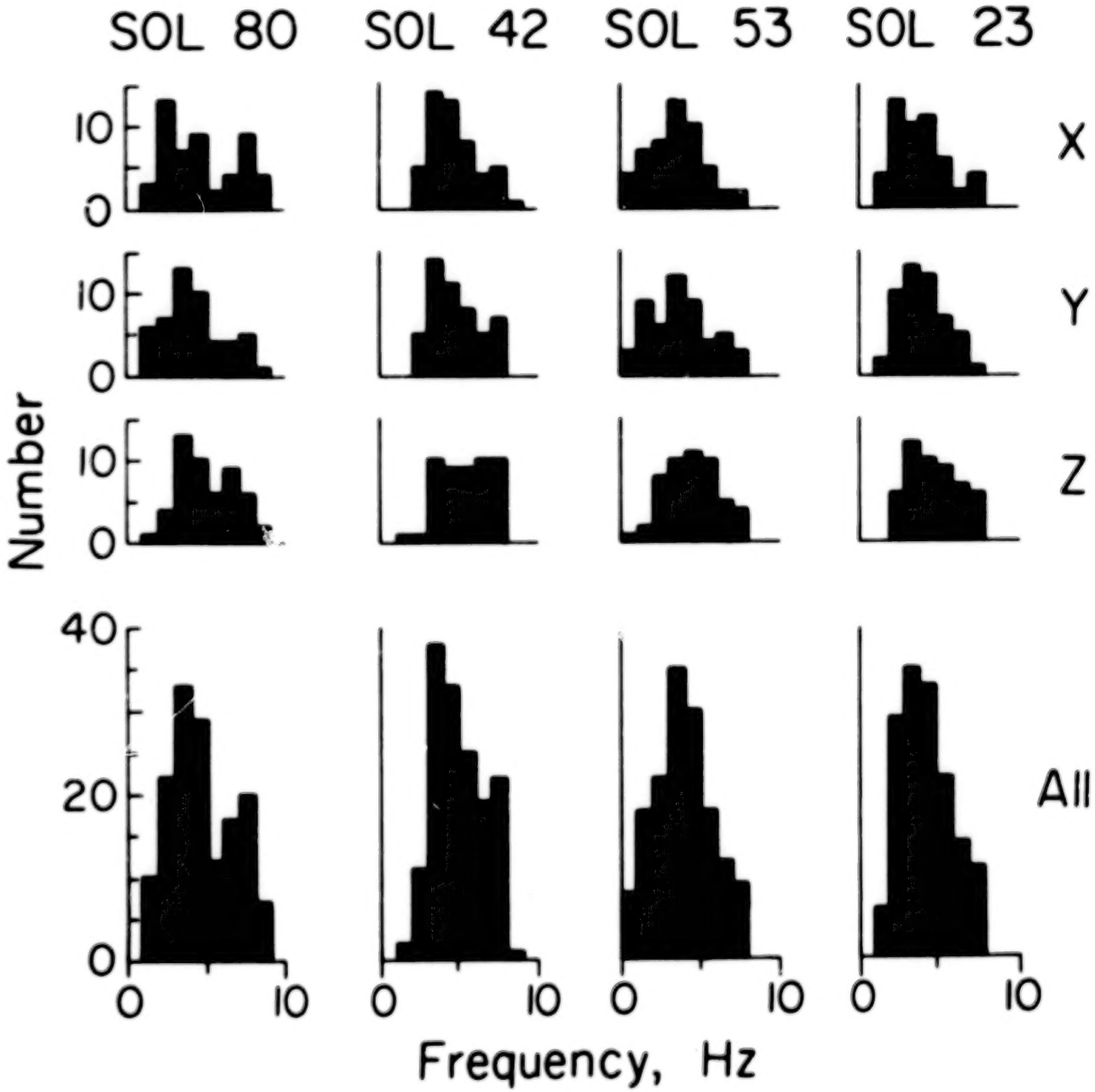
Figure 2. The SOL 80 compared with similar events recorded to southern California by a Viking seismometer located at the California Institute of Technology. All events are recorded in the event mode (Anderson *et al.*, 1977).

Figure 3. Histograms of the SOL 80 axis crossings compared with histograms from three other events. The SOL 80 event is noticeably richer in high frequencies (Anderson *et al.*, 1977).


SOL 80 EVENT
X-AXIS
Y-AXIS
Z-AXIS
AMPLITUDE
FREQ
1
2
P
S
0
10
20
30
40
50
60
70
80
90
100
110
120
130
TIME (SECONDS)



EVENT MODE COMPRESSED DATA


SOL 80
SOL 42
SOL 53
SOL 23
X
Y
Z
All
Number
10
0
40
20
0
10
Frequency, Hz

APPENDIX A

List of Personnel

Don L. Anderson - California Institute of Technology

Frederick K. Duennebier - University of Hawaii

M. Nafi Toksoz - Massachusetts Institute of Technology

Gary V. Latham - University of Texas

Robert L. Kovach - Stanford University

George H. Sutton - University of Hawaii

Frank Press - Massachusetts Institute of Technology

Yosio Nakamura - University of Texas

Andrew R. Lazarewicz - University of Hawaii

Wayne F. Miller - California Institute of Technology

Tony C.D. Knight - Martin Marietta Aerospace Corp.

Anton M. Dainty - Georgia Institute of Technology

Neal R. Goins - Massachusetts Institute of Technology

Ken Anderson - Massachusetts Institute of Technology

Sid Cook - Martin Marietta Aerospace Corp.

Wyatt Underwood - Martin Marietta Aerospace Corp.

Michael Sherrard - Martin Marietta Aerospace Corp.

Don Mullins - Martin Marietta Aerospace Corp.

James Stephens - Martin Marietta Aerospace Corp.

William Mair - Martin Marietta Aerospace Corp.

Francis L. Lehner - California Institute of Technology

J. Lewko - Bendix Corp.

D. Gibson - Bendix Corp.

M. Van Dyke - Bendix Corp.

T. Gaffield - Bendix Corp.

D. LaFrenierer - Bendix Corp.

C. Lee - Viking Project Office

American Microsystems Inc.

APPENDIX B

Software Filter Control

This Appendix demonstrates how a given transfer function (of a filter, amplifier, etc.) is converted to hardware and/or software design. The background materials for this Appendix may be found in Lazarewicz and Miller (1979).

Generalized First-Order Transfer Functions

$$F(s) = \frac{a_o + a_1 s}{b_o + b_1 s} = \frac{a_1 (s + a_o/a_1)}{b_1 (s + b_o/b_1)}$$

Usually F(s) is given or known by one of these representations.

s = Laplace variable. Let $A = a_o/a_1$, $B = b_o/b_1$.

Bi-linear z-transform:

$$\left[s \longrightarrow \frac{1 - z^{-1}}{1 + z^{-1}} \right] \qquad A, B \longrightarrow \tan^{-1} \left(\pi \frac{A,B}{\omega_s}\right) = A', B'$$

z^{-1} = unit time delay operator

(A,B in radians/sec)

ω_s = sampling frequency $(\frac{\text{radians}}{\text{sec}})$

Note: A, B, ω_s must all be in same units.

$$F(z^{-1}) = \frac{a_1}{b_1} \left[\frac{\frac{1 - z^{-1}}{1 + z^{-1}} + A'}{\frac{1 - z^{-1}}{1 + z^{-1}} + B'} \right]$$

$$= \frac{a_1}{b_1} \left[\frac{(A' + 1) + (A' - 1)\, z^{-1}}{(B' + 1) + (B' - 1)\, z^{-1}} \right] = \frac{w}{v}$$

v = input discrete time series

w = output discrete time series

$$= \frac{a_1 (B' + 1)}{b_1 (A' + 1)} \left[\frac{1 + \left(\frac{A' - 1}{A' + 1} \right) z^{-1}}{1 + \left(\frac{B' - 1}{B' + 1} \right) z^{-1}} \right]$$

$$= \alpha \left[\frac{1 + \beta z^{-1}}{1 + \gamma z^{-1}} \right]$$

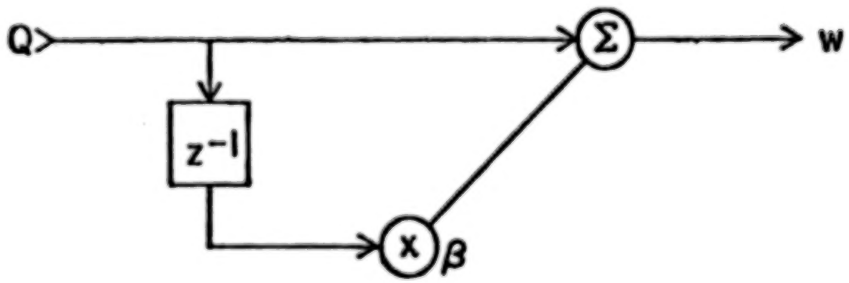
where

$$\alpha = \frac{a_1 (B' + 1)}{b_1 (A' + 1)} \qquad \beta = \frac{A' - 1}{A' + 1} \qquad \gamma = \frac{B' - 1}{B' + 1}$$

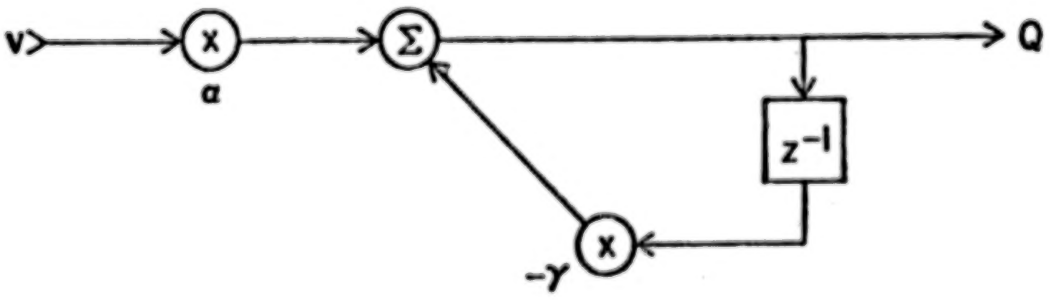
Define $Q = \dfrac{\alpha v}{1 + \gamma z^{-1}}$

$$\Rightarrow w = Q + \beta z^{-1} Q$$

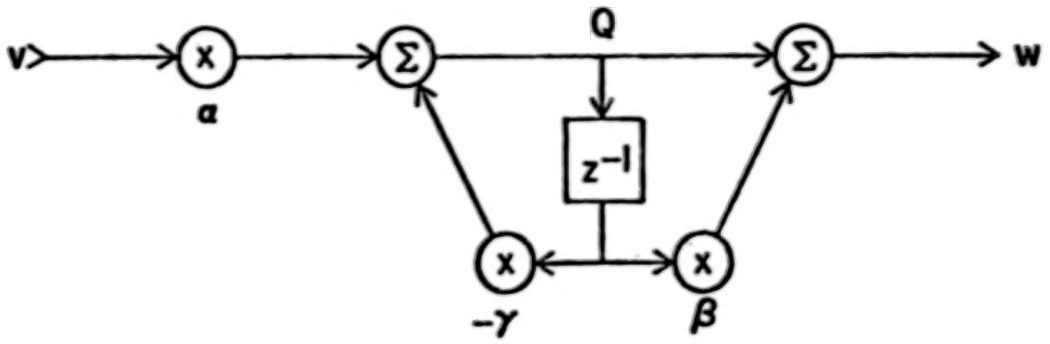
Now, build a state diagram from this equation:



but $Q = \alpha v - \gamma z^{-1} Q$



Combining the two portions of this state diagram



$\boxed{z^{-1}}$ is a unit time delay of the value Q, in other words, the output of $\boxed{z^{-1}}$ is the previous value of Q.

This state diagram, through suitable choices of α, β, γ, can represent any first-order transfer function (e.g., filter, amplifier).

Generalized Second-Order Transfer Functions

$$F(s) = \frac{a_o + a_1 s + a_2 s^2}{b_o + b_1 s + b_2 s^2} = \frac{a_2 (s + A_1)(s + A_2)}{b_2 (s + B_1)(s + B_2)}$$

where

$$A_{1,2} = \frac{a_1 \pm \sqrt{a_1^2 - 4 a_o a_2}}{2 a_2}$$

$$B_{1,2} = \frac{b_1 \pm \sqrt{b_1^2 - 4 b_o b_2}}{2 b_2}$$

As in the first-order case, F(s) is usually given or known in one of these two forms.

Bi-linear z-transform:

$$s \rightarrow \frac{1 - z^{-1}}{1 + z^{-1}} \qquad A_{1,2}, B_{1,2} \rightarrow \tan^{-1}\left(\pi \frac{A_{1,2}, B_{1,2}}{\nu_s}\right) = A'_{1,2}, B'_{1,2}$$

$$F(z^{-1}) = \frac{a_2}{b_2}\left[\frac{\left(\frac{1-z^{-1}}{1+z^{-1}} + A_1'\right)\left(\frac{1-z^{-1}}{1+z^{-1}} + A_2'\right)}{\left(\frac{1-z^{-1}}{1+z^{-1}} + B_1'\right)\left(\frac{1-z^{-1}}{1+z^{-1}} + B_2'\right)}\right]$$

$$= \frac{a_2}{b_2}\left[\frac{\left[(A_1' + 1) + (A_1' - 1)\, z^{-1}\right]\left[(A_2' + 1) + (A_2' - 1)\, z^{-1}\right]}{\left[(B_1' + 1) + (B_1' - 1)\, z^{-1}\right]\left[(B_2' + 1) + (B_2' - 1)\, z^{-1}\right]}\right]$$

which reduces to:

$$F(z^{-1}) = \alpha\left[\frac{1 + \beta\, z^{-1} + \delta\, z^{-2}}{1 + \gamma\, z^{-1} + \varepsilon\, z^{-2}}\right] = \frac{w}{v}$$

where

$$\alpha = \frac{a_2\,(B_1' + 1)(B_2' + 1)}{b_2\,(A_1' + 1)(A_2' + 1)}$$

$$\beta = \frac{(A_1' + 1)(A_2' - 1) + (A_1' - 1)(A_2' + 1)}{(A_1' + 1)\,(A_2' + 1)}$$

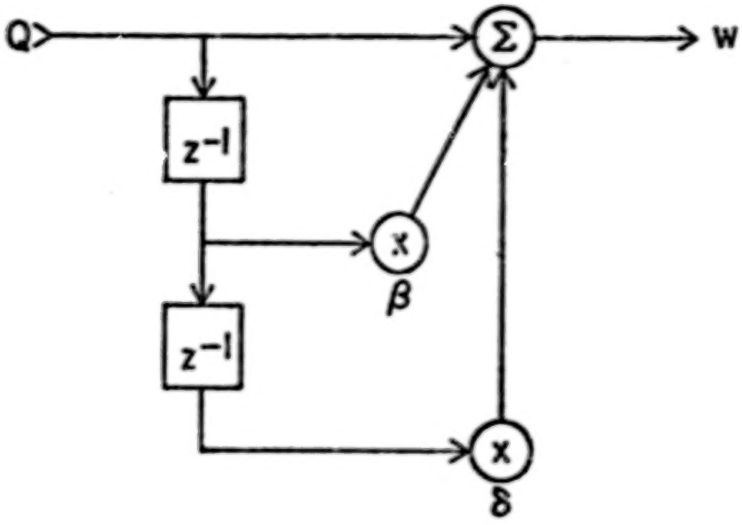
$$\gamma = \frac{(B_1' + 1)(B_2' - 1) + (B_1' - 1)(B_2' + 1)}{(B_1' + 1)\quad(B_2' + 1)}$$

$$\delta = \frac{(A_1' - 1)(A_2' - 1)}{(A_1' + 1)(A_2' + 1)} \qquad \varepsilon = \frac{(B_1' - 1)(B_2' - 1)}{(B_1' + 1)(B_2' + 1)}$$

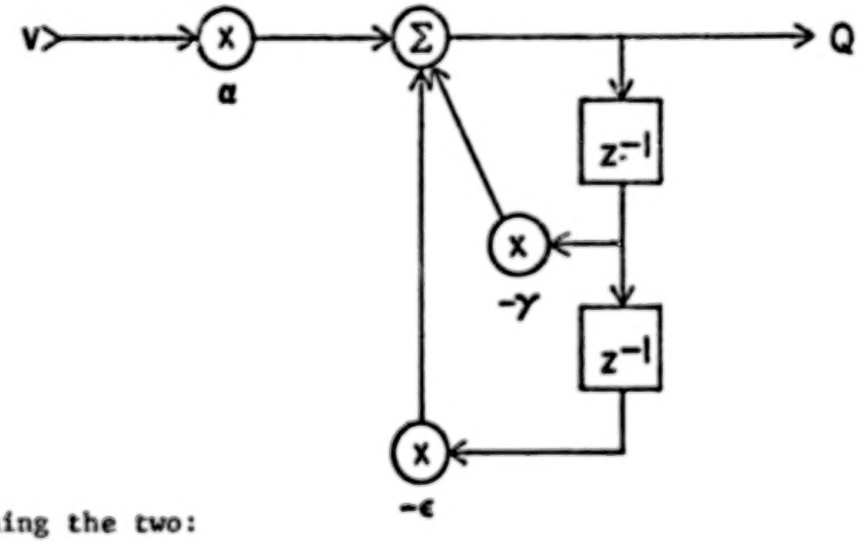
Define $Q = \dfrac{\alpha\, v}{1 + \gamma\, z^{-1} + \varepsilon\, z^{-2}}$

$$\Rightarrow w = Q + \beta\, z^{-1}\, Q + \delta\, z^{-2}\, Q$$

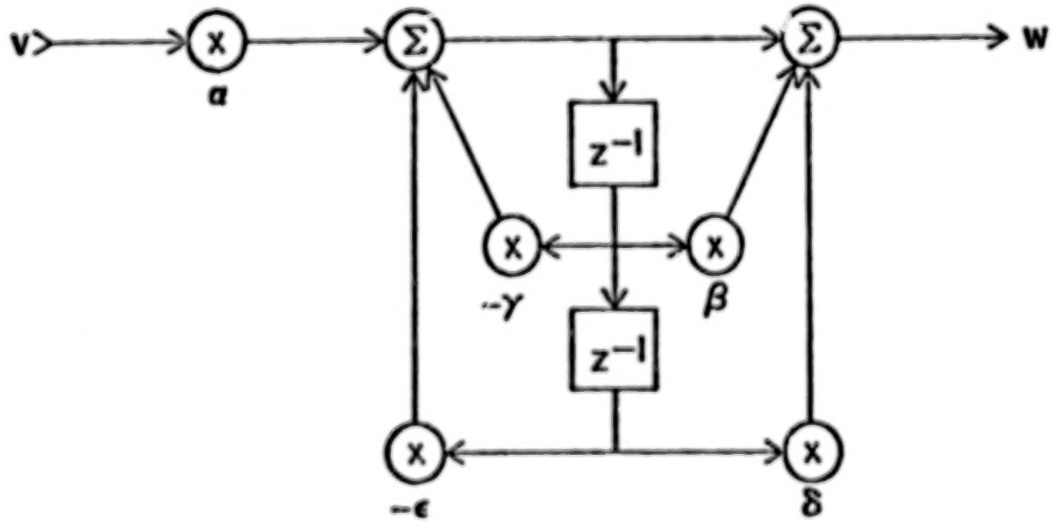
Again, building a state diagram:



but $Q = \alpha v - \gamma z^{-1} Q - \epsilon z^{-2} Q.$



Combining the two:



Again, the output of $\boxed{z^{-1}}$ is its previous input.

This state diagram, through suitable choices of α, β, γ, δ, ϵ can represent any second-order transfer function.

Any transfer function can be broken up into a combination of first- and second-order transfer functions. Therefore, an appropriate cascade of these state diagrams can be made to represent any transfer function. Converting a state diagram into electronic hardware is a straightforward process, and has been used to design and build the Low-pass Butterworth filters on the Viking seismometer instrument.

The constants $\alpha,\ldots,\epsilon$ in the seismometry package were hard-wired and only offered a choice of corner frequencies for the Butterworth filters. However, these constants need not be hard wired, they can be software modifiable.

We recommend that any future seismometer package have an appropriate number of cascaded stages, where the filter (or amplifier) parameters, and the number of stages to be used, are adjustable by Earth-based commands. The additional flexibility in such a system will far outweigh the engineering required to implement such a system.

APPENDIX C

This appendix is included to illustrate a possible approach to *in situ* data management. This approach is not included as a formal recommendation, but rather as what some team members consider a promising idea.

Priority Data Recording

The fast-growing microprocessor technology and the advent of the bubble memory allows consideration of a new approach for data management. This approach is Priority Data Recording (referred to here as PDR) and takes advantage of substantially increased data storage space available on the lander. Incoming signals are constantly assigned a priority value based on a combination of any number of criteria: amplitude and/or frequency content, time of day, simultaneous detection elsewhere in the seismic network, etc. Incoming data are continuously stored in memory, with higher priority data recorded at the expense of the lowest priority recorded data. It may even be feasible to change priorities (e.g., by simultaneous detection by another instrument). When downlinking of data to Earth occurs, the highest priority data come first. Even in the downlinking process, a great deal of flexibility is available; for example, lower priority data may be sent during times of high bit error rates, events of medium or low priority may be downlinked many days after detection if their priority in the recorded data stack increases, high priority data could be saved until successful downlinking is confirmed, data recorded previous to and after the event could be held in memory and downlinked on Earth command if the scientists wish to see those data. Thus the data management could be very flexible.

The great advantage of such a system is that all events downlinked are not compressed, therefore considerably easier to analyze. Of course, it is also possible to compress low priority data if desired. Looking through the Viking seismology data, it becomes quite obvious that much more data space could have been utilized for quiet time Event or HDR mode recording if only the wind noise data could have been edited out before downlinking. With PDR, a signal sent from a wind indicator to the seismometer package could depress the priority level during windy periods. Such an "anti-trigger" signal could also originate from other spacecraft operations (e.g., the Viking imaging system generated such a signal), thus automatically reducing the amount of recorded noise.

The disadvantage of the PDR system is the possibility of misassigning priorities; in other words, that the priority of a given signal is not proportional to its importance. The problem of how to assign priorities is one which deserves considerable attention. If the system for assigning priorities is iteslf flexible, then the priority assignments could change as the mission progresses. Thus early in the mission more effort would be spent on defining the overall nature of signals, and as it becomes more evident which signals are more desirable, the PDR system would be modified to favor those signals.

Obviously, the development of a PDR system requires much study and can't be included in much detail in this report, but it is a promising approach. The following two sections are 1) a simple approach to demonstrate how such a system might work, and 2) a copy of a discussion of seismic event detection and data compression for a penetrator network. The latter is duplicated from a Bendix Corp. report.

PRIORITY DATA COLLECTION

A SIMPLE EXAMPLE

The problem is to assign a priority to all incoming signals and retain only the ones with the highest priority. The simplistic system described here is designed to illustrate how such a system might work.

Assume four triggers operate on the input signal. Depending on the "strength" of the trigger, each trigger may produce a value T_i (i=1,4) ranging from 0 (off or very low) to 3 (essential). Keeping track of the trigger level in a shift register, the value of T_i is shifted left by W_i bits, where W_i (i=1,4) ranges from 0 to 3 and indicates the relative importance of the trigger. Thus the weighted trigger level is $2^{W_i} \times T_i$. The four weighted triggers are then summed, so the total priority is $P = \Sigma(2^{W_i} \times T_i)$ and varies from 0 to 64, requiring 8 bits. The total memory space would be divided into blocks of data where an entire block is written (higher priority overwriting the lowest priority data still in memory) at a time. Order of the blocks is unimportant, as each contains a time tag, and thus could be reordered after receipt on Earth. One block of data might hold 84 samples from each of three axes, each sample having 8 bits. Each block also contains the 8 bit priority count and a 24 bit time code (as was used in the Viking system). Thus a total of 2048 bits are required per block. A collection of 1000 blocks of data would require 2.05×10^6 bits (the Viking seismometer nominal allocation was 1.1×10^6 bits per SOL). At a sampling rate of 20 Hz, a total of 70 minutes of data would be stored at any given time. Although this isn't very much, in principle, it contains the most interesting data collected since the last data transmission from the spacecraft.

PDR for Planetary Penetrator Missions

This last portion of this appendix is entirely reproduced, with permission, from Thomas and Perkins (1977).

Seismic Event Detection and Data Compression

The major problems in penetrator data handling arise from the seismology experiment and are (a) determining when a seismic event has occurred, (b) ensuring that the full extent of the event is recorded but without including an excessive amount of pre- and post-event routine microseismic background, and (c) compressing the data to the maximum extent possible without losing the features of interest to the seismologist. Also of importance, but of lesser difficulty, is (d) the question of how to assess candidates for "bumping" if the amount of event data exceeds the capacity of the memory, or, alternatively whether bumping is in fact desirable.

Consider problem (c) first, i.e., compression and the essential features of a seismic event. A common characteristic of all seismic event data is that they are oscillatory. In Viking only the envelope and freqeuncy of zero-crossings are transmitted, which allows considerable data compression but loses details of multi-component waveforms and the sense of the initial deflections. In the Viking implementation of envelope generation there is also an unsatisfactory low frequency response. If only the envelope and zero-crossings of the currently dominant component are transmitted it may be difficult to determine the precise times of arrival of overlapping trains of oscillations, as might occur with the P, S and L waves of a nearby event. In seeking a seismic data system for the penetrator it is necessary to find an acceptable compromise between the need for improved fidelity

of waveform and the need to keep the total data within the capacity of the memory, bearing in mind the probable number of events per day and the fact that a "compression" technique which is applied to data for which it is not suitable can actually increase rather than decrease the number of bits which must be transmitted. The proposed solution is to detect successive maxima and minima in the seismic waveforms and to transmit their amplitudes and the intervals between them, without further compression. Compression of a single-frequency oscillation which increases and decreases in amplitude in a well-ordered manner is relatively simple, using "delta" compression for the periods between rectified peaks and a first- or second-order predictor for the amplitudes. However, worthwhile additional compression of maxima, minima and interval data for a complex waveform is impossible without passing the data at least twice more through the microprocessor--once to perform a Fourier-type analysis on the intervals between peaks in order to determine the principal components, the second time to separate the components and to apply individual delta/predictor compressions to them. Such off-line processing does not appear to be a practical proposition for the penetrator. Even with a Fourier analysis the overlapping of two oscillations of similar periods and amplitudes, but different phases, can lead to erroneous results, although the human eye and brain would have little difficulty in determining what was happening.

The technique of transmitting only maxima and minima loses the precise details of the shape of each oscillation but it is understood that that is in any case of small importance to the seismologist provided that polarity, amplitude, period and time of occurrence are retained. It also appears to

be the most economical method of preserving small, high frequency signals riding on a larger, low-frequency signal. As with any other efficient compression technique the amount of data to be transmitted is sensitive only to change, not frequency. Thus if one signal is at 10 Hz and dies out in 100 cycles (i.e., 10 seconds) the amount of data transmitted will be exactly the same as for a signal at 0.1 Hz which also dies out in 100 cycles (i.e., 1000 seconds). A composite waveform of those two components would in general require precisely twice the amount of data to be transmitted, although coincident peaks could in some cases cause a small reduction.

The detection of maxima and minima could be performed by either an analog or a digital method, the latter involving the microprocessor for the decision process. Provided that it can be shown that the microprocessor would not be overloaded, the digital method is definitely to be preferred. The highest frequency of interest is 10 Hz, and sampling at 100 times per second per channel the maximum amplitude and phase errors in detecting a noise-free maximum or minimum are 5% and 18 degrees, respectively. At a total sampling rate of 300 per second for the three channels the microprocessor will not be anywhere near saturation, even including the simple max/min decision algorithms. In order to detect only the event peaks the difference between successive selected max/min points will be required to exceed (TBD) times the microseism background RMS value established during the immediately preceding non-event period.

Two words are required for each selected point (i.e., an amplitude and an interval), and there are two points per cycle. At four words per cycle and 10 bits per word a 10 Hz event lasting for 5 minute in all three channels would require 360,000 bits. With at least 1.2×10^6 bits per day available for seismic use, once the immediate pre- and post-impact priority operations

are completed, it will be seen that about 3-4 such events could be covered each day. If the frequency is assumed to be 0.3 Hz and the duration 1 hour, in three channels, then 8-9 events can be covered.

If the amount of seismic data exceeds the capacity of the system, or if it is required simply to characterize the microseismic background, it is relatively simple to command the microprocessor to average the amplitude moduli and peak-to-peak intervals over selected periods in order to obtain the equivalent of the much more compressed envelope and average frequency type of information.

In order that the max/min method can work as described and to avoid aliasing, it is essential that the A/D converter is preceded by an analog filter cutting off fairly sharply above 10 Hz.

Since the peak-to-peak interval data can potentially cover three decades for the same event, the 10 bits of the word should be allocated 2 bits to the decade, 8 bits to the interval, for a potential accuracy of 0.4%, which should be more than adequate.

In deciding whether a significant seismic event has occurred (i.e., problem 'a') the fundamental question of what is a "significant event" immediately arises. The most obvious answer is that it is a (relatively) short-period occurrence that differs statistically from the continuous micro-seismic background. In the general context of seismic signals it appears to be adequate to discriminate on the basis of amplitude alone, but to avoid too high a false alarm rate it is necessary to smooth out the effects of isolated microseismic noise peaks. The proposed method of seismic event detection for the penetrator is to compare the outputs of short-period and long-period filters applied to the rectified max/min amplitude data. The simplest and

computationally the most economical type of filter is exponential, of the form

$$y_n = K \cdot x_n + (1 - K) \cdot y_{n-1}$$

where

y_n = current value of filter output

y_{n-1} = previous value of filter output

x_n = current rectified max/min amplitude input

K = constant in range 0 to 1

For a step input of magnitude 'A' the output 'y_s' at step 's' is given approximately by

$$y_s = A(1 - e^{-ks})$$

A small value of K gives a slow response, and conversely a larger value of K gives a more rapid response to changes in amplitude. Since the filter computation in the penetrator steps only when a new maximum or minimum is detected, and not at regular time intervals, the "time-constants" of the filter are not measured in absolute time, but in terms of numbers of peak detections; they are therefore automatically self-adaptive to the frequency of oscillation of the event. An event at 0.01 Hz is detected as easily and in the same number of filter steps as an event at 10 Hz, given the same signal increase per cycle. The optimum values of K for the long-period and short-period filter require further study. It is suggested tentatively that values of 0.001 and 0.07 might be appropriate, but they should in any case be adjustable by Earth command, after assessment of actual conditions following emplacement on Mars. If the short-period constant is made too small and/or too similar to the long-period constant then the required difference threshold between the outputs might not b

reached for an even with a very slow increase in amplitude. However, in the seismograms which have been examined so far it appears that the maximum amplitude is generally reached within a few cycles and that particular problem is unlikely to arise in practice.

In order to avoid the loss of data corresponding to the start of an event, which is of particular interest to the seismologist (i.e., problem b), each amplitude/interval pair of words corresponding to a max/min detection will be inserted into a serial register delay line, or a reserved block in the microprocessor memory, the length of the delay being determined by the slowest anticipated rate of rise of the signal (in cycles, not seconds), the "time constant" of the short period filter, and the difference threshold required for event detection. Bearing in mind that both the data delay line and the detection filters will be stepped by max/min detections and will automatically adapt to the frequency of oscillation, it is relatively easy to decide that a delay of 50 points (i.e., 25 maxima and 25 minima, plus intervals--1000 bits total) should be adequate to ensure that the start of the event is retained. When the event detector triggers, the penetrator time reference will be sampled and temporarily stored in the computer memory. The event time and the delay line data will be formatted behind a telemetry frame header and inserted into one of the sections of the bubble memory. All further max/min detection data will be inserted into the bubble memory as well as the delay line, but in the required telemetry format, until the end of the event is detected (see discussion below). The time reference inserted at the start of the event data corresponds to the time at which the detector triggered, not to the time of the start of the event. An identifiable dummy set of max/min/interval words will be inserted into the data stream, at the end

of the delay line contents, to show the position to which the time tag corresponds. Once the PI seismologist has decided where the event started its true time can be determined by subtracting all the interval data between that point and the triggering point from the time tag. In order to prevent a build-up of seismic signal timing errors due to bit-errors during the transmission it is recommended that the first maximum or minimum in each frame has associated with it the corresponding full 31-bit time reference, in addition to the time interval since the previous minimum or maximum.

The detection of the end of an event is not quite as simple as the detection of its beginning. If it can be assumed that the non-event micro-seismic background is constant, or at least varies a negligible amount during an event, then it may also be assumed that the event is over when the output of the short-period filter falls back to the level which the long-period filter had before the event started. Note that by the time the event is detected the output of the long-period filter may already have been influenced by it to a noticeable extent. To avoid a premature data recording cut-off it is proposed that the long-period filter output which is stored as the reference should not be the value at the time of event detection, but a previously stored value delayed for a number of steps comparable with the number required to detect an event after its onset--for example, 20 max/min detections. A delay-line is not necessary; by definition, the output of the long-filter is intended to be a very slowly varying background reference, and a single value selected every 20 max/min detections and held for 20 before use should be adequate.

At the end of the event the long-period filter output will probably still be showing a significant deviation from the true background noise value,

which could tend to obscure a second event occurring shortly after the first. To reduce that probability the output of the long-period filter should be reset to the stored value, and recording of data should continue for at least 10 max/min detections, and following that until there is no significant difference between the outputs of the long-period and short-period filters for at least 10 steps.

If the assumption that the microseismic background is constant is invalid, and the background level increased significantly during the event, then the system described above would fail to switch off. Although the output of the short-period filter would fall to the current noise level it would still exceed the stored reference value, and hence the initial "end-of-event" criterion would not be satisfied. Two solutions are possible. In the first the reference level could be commanded to a fixed value which is judged to be greater than any background noise but less than any event of interest. In the second the output of the long-period filter could be automatically tracked during non-event periods to establish the peak-value to date, and that level (possibly multiplied by some factor) could be used as the end-of-event reference. In either case the requirements to continue recording for 10 max/min etections, and then further until the outputs of the two filters were not significantly different would be retained. When the system determines that the event has ended the current telemetry frame is completed with blanks, and the search for new events resumes.

If the background noise level proves to be so small that the system ceases to detect maxima and minima, and the specified 20 post-event detections do not occur, then the system will remain in the event mode indefinitely. However, since data are stored only when a maximum or minimum is detected

there will be no overflow of useless data into the bubble memory and delay line. If another event should occur with the system in that state then it must be triggered into a new event mode by specifying that an old event can also be terminated if the short-period filter output returns above the previous reference level and the two filter outputs are significantly different. It is necessary to trigger a new event mode, rather than simply to continue recording in the old event mode, in order to obtain an accurate time tag.

The final problem, (d), in seismic data handling is whether data already stored should be replaced by new event data when the memory is full, and, if so, how the relative priorities should be determined. An associated problem is how to organize the serial bubble memory so that one set of event data can replace another of probably different length. From the purely seismic point of view an event can be assessed only after it is finished, or at least well underway. Thus once the bubble memory becomes completely full the decision must be made immediately as to which set of data is to be eliminated if a new set arrives, or, alternatively, it must be decided to accept no more data until after the current batch has been transmitted. It is quite possible that if one set is displaced by a new set it may subsequently be found that the new set rates a lower priority value than the set it displaced. The importance of a set of event data is not simply a function of its own properties, such as amplitude, frequency, duration, etc., but also, and perhaps more so, a function of its relation in time to other events detected at the same penetrator and at other penetrators. The coordination of the results from a network gives far more information than the sum of individual assessments from each penetrator separately. If each penetrator is allowed to make priority decisions independently of the others then all that may be received in an

active situation is a collection of P, S and L wave traces, which may be difficult to distinguish one from another, and in which there may be no complete set for a particular event. Since it appears to be often the case that the S waves are larger in amplitude than the P waves, and the L waves may be larger than the S waves, then a simple amplitude priority scheme would eventually build up a collection consisting mainly of L waves, with perhaps a few S's. It is recommended that unless there is a definite reason to assess data as questionable then all data sets satisfying the event criteria should be stored until transmitted to the orbiter, and that no priority "bumping" scheme should be implemented. In this way the probability of obtaining a coordinated and complete picture of at least one event from all sources will be maximized, even though the wave traces at the more distant penetrators may be only just above the level of detectability, and would almost certainly be displaced in a priority scheme by a different, nearby event.

The grounds for rating data as questionable or of little use are (a) intense meteorological activity, e.g., strong winds, dust storms, and (b) mechanical activity within the penetrator itself, e.g., drilling operations. The latter is a very obvious case, and it is recommended that the seismometer is switched off, or alternatively that no data are stored in such circumstances. The assessment of the effect of meteorological activity requires first of all appropriate sensors on the afterbody, and then correlation of their readings with the seismic outputs to determine if there really is significant penetration of disturbances to the depth of the seismometer. Wind velocity is best determined by an anemometer, but it could also possibly be inferred from pressure sensor fluctuations due to turbulence, provided

that the pressure sensor was sufficiently sensitive and had an adequate frequency response. If it is established that meteorological disturbances do affect the seismometer, then the threshold for event decisions during such disturbance will have to be set correspondingly higher. However, it should be noted that this may occur automatically since the long-period filter output and the short-period filter output will track the temporarily increased background signal. In order that the background reference is not permanently offset to a level much higher than the true microseismic background the detection of high level meteorological activity should be used to inhibit permanent adjustment of the long-term background reference level.

If the recommendation not to implement a priority system is unacceptable, then the simplest approach is to classify event data sets into 3 or 4 PI-defined priority levels and to insert data at each level into a separate section of the multi-section bubble memory. When a particular section becomes filled then data which would otherwise be inserted into that section is inserted into the lowest priority section, if necessary overwriting data already there. When the lowest priority section becomes filled entirely with higher priority data it is inhibited from further activity, and high priority overflow is diverted to the next level section, and so on. Since, as mentioned earlier, an event's priority can be assessed only after it is completed, a blank serial store must always be available into which the latest set of data can be run, for assessment before deciding to dump or retain.

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA CR-3408		

4. Title and Subtitle	5. Report Date
THE VIKING SEISMOMETRY FINAL REPORT	April 1981
	6. Performing Organization Code

7. Author(s)	8. Performing Organization Report No.
Andrew R. Lazarewicz, Don L. Anderson, Kenneth Anderson, Anton M. Dainty, Frederick K. Duennebier, Neal R. Goins, Tony C. D. Knight, Robert L. Kovach, Gary V. Latham, Wayne F. Miller, Yosio Nakamura, George H. Sutton, and M. Nafi Toksoz	10. Work Unit No.

9. Performing Organization Name and Address	11. Contract or Grant No.
NASA Office of Space Science Planetary Division, Viking Program Washington, DC 20546	NAS7-100
	13. Type of Report and Period Covered
12. Sponsoring Agency Name and Address	Contractor Report
National Aeronautics and Space Administration Washington, DC 20546	14. Sponsoring Agency Code

15. Supplementary Notes

Headquarters Technical Monitor: Joseph Boyce
Final Report

16. Abstract

The purpose of the Viking Seismology Experiment was to determine the seismicity of Mars and define its internal structure by detecting vibrations generated by marsquakes and meteoroid impacts. The lack of marsquakes recognized in the Viking data makes it impossible to make any direct inferences about the interior of Mars and only allows the setting of upper bounds on the seismic activity of the planet. After obtaining more than 2100 hours (89 days) worth of data during quiet periods at rates of one sample per second or higher, the Viking 2 seismometer was turned off as a consequence of a lander system failure. During the periods when adequate data were obtained, one event of possible seismic or meteoroid impact origin was recognized; however, there is a significant probability that this event was generated by a wind gust. The lessons learned from Viking, however, will ensure that seismic systems on future Mars missions will have a considerably higher probability of obtaining their goals.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Mars Seismometry Viking	Unclassified - Unlimited Subject Category 91

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	54	A04

* For sale by the National Technical Information Service, Springfield, Virginia 22161

NASA-Langley, 1981

END

June 18, 1981